PATENT SPECIFICATION

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(19)

1 539 028

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(54) IMPROVEMENTS IN OR RELATING TO OPTICAL SYSTEMS

(71) I, THE PRESIDENT OF THE TOKYO INSTITUTE OF TECHNOLOGY, of 12-1 Ookayama 2-chome, Meguro-ku, Tokyo, Japan, a Japanese Juridical person, do hereby declare the invention, for which I pray that a patent may be granted to me, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to integrated optical circuits.

According to the invention there is provided an integrated optical circuit comprising a multi-hetero structure waveguide and a mesa type thin-film optical oscillator integrally formed through a directional coupler upon the waveguide, the dimensions of the oscillator and waveguide being so selected that the wavelength of the light signal generated by the oscillator can be coupled to the waveguide for transmission by the waveguide with substantially no initial loss.

According to the invention, there is further provided a method of making an integrated optical circuit comprising the steps of preparing a multi-layered wafer consisting of a first layer of GaAs, a second layer of $Al_zGa_{1-z}As$, a third layer of $Al_xGa_{1-x}As$, a fourth layer consisting of $Al_zGa_{1-z}As$ and constituting a coupling layer, a fifth layer consisting of $Al_yGa_{1-y}As$ and constituting an output waveguide, a sixth layer consisting of $Al_zGa_{1-z}As$ and a seventh layer of GaAs, the first to seventh layers being stacked one on top of the other in the recited order from the top to the bottom; placing a mask on the first layer; back-sputter-etching the wafer so as to remove the unmasked layers above the lower half portion of the coupling layer consisting of $Al_zGa_{1-z}As$ thereby forming a mesa type oscillator; thereafter finishing the opposite end faces of the first to third layers to have a mirror surface; attaching transparent insulating layers upon the said end faces and forming reflecting mirrors on the transparent insulating layers to complete the formation of a mesa type oscillator, the dimensions of said layers being so selected that the wavelength of the light signal generated by the oscillator can be coupled to the waveguide for transmission by the waveguide with substantially no initial loss.

Integrated optical circuits embodying the invention will now be described, by way of example, with reference to the accompanying diagrammatic drawings in which:

Figure 1 is a perspective view of one of the optical circuits;

Figure 2 is a chart showing the relationship between the refractive indices of the different layers of the circuit shown in Figure 1;

Figure 3 is a schematic representation of the circuit shown in Figure 1;

Figures 4 and 5 are wave diagrams illustrating the optical waves as they propagate in the circuit of Figure 1;

Figures 6(a) and 6(b) are wave charts illustrating the relationship between the propagation constants and waveforms;

Figure 7 illustrates the different steps in the manufacture of the circuit of Figure 1; and

Figures 8 to 19 are sections through further ones of the optical circuits.

The integrated optical circuit of Figure 1 comprises an optical oscillator 10 coupled to an optical waveguide 10. The oscillator 10 includes a GaAs layer 11, an $Al_zGa_{1-z}As$ layer 12 and an active layer 13 consisting of $Al_xGa_{1-x}As$, stacked one on top of the other in the stated order. A first electrode 14 covers the uppermost layer 11 of the stack, reflecting mirror layers 16 and 16*a* lie on opposite sides of the stack separated from the stack by respective transparent insulating layers 15 and 15*a*. The waveguide 20 includes an $Al_zGa_{1-z}As$ layer 21 which acts as a coupling layer for providing an optical coupling between the oscillator 10

and the waveguide 20, an $Al_yGa_{1-y}As$ layer 22 which acts as the layer along which light is transmitted by the waveguide, an $Al_zGa_{1-z}As$ layer 23, a GaAs layer 24 and an electrode 25 stacked one on top of the other in that order. The subscripts x, y and z have the following relation:

$$x<y<z$$

The relationship between the refractive indices of the seven different layers is illustrated in Figure 2, where *p* and *n* denote the types of semiconductor each layer forms.

The operation of the optical circuit of Figure 1 will be described with reference to Figures 3 and 4. The coupling length l_c depends upon the thicknesses 2*a*, 2*b* and 2*c* and the refractive indices n_1, n_2 and n_3 respectively of the active layer 13, the output waveguide layer 22 and the coupling layer 21. The symbols B_1, B_2 and B_3 represent respective propagation constants within the three layers.

A laser wave A_1 with the coupling length l_c produced at one end of the oscillator 10 propagates in the direction indicated by the associated arrow (from left to right) and gradually changes into the laser wave A_2. Part of this laser wave propagates into the waveguide 20 as the laser wave A_3 which is transmitted along the layer as the output of the oscillator. Within the oscillator 10, the laser wave is reflected by the reflecting mirror 16*a* to form a laser waveform A_{1a} indicated by broken lines. The laser wave A_{1a} changes into the laser wave A_{2a}, part of which is propagated into the waveguide 20. The laser wave A_{3a} is reflected at the reflecting mirror 16 to form the laser wave A_1 again indicated by the solid line.

The propagation of laser wave when the coupling length is $l_c/2$ and the reflector 16 is extended to close one end of the wave guide is shown in Figure 5. The laser waves are shown as the superimposition of two waves, see Figure 6(a) for the case when $B1=B2$ and Figure 6(b) for the case when $B1\neq B2$.

The optical oscillator and the waveguide are both thin film devices having a small loss at the operational wavelength and so can be manufactured as an integrated multilayered structure. As can be seen in Figures 4 and 5 the oscillator produces a light signal having a wavelength such that when it is coupled to the waveguide it can be transmitted along the waveguide with substantially no initial loss.

A method of manufacturing the optical circuit of Figure 1 will now be described with reference to Figure 7. Initially a wafer is produced consisting of the successive layers the GaAs layer 11, the $Al_zGa_{1-z}As$ layer 12, the $Al_xGa_{1-x}As$ layer 13, the $Al_zGa_{1-z}As$ layer 21, the $Al_yGa_{1-y}As$ layer 22, the $Al_zGa_{1-z}As$ layer 23 and the GaAs layer 24 (see step (i) in Figure 7). A mask 26 is then placed on the layer 11 as shown in step (ii) Figure 7.

The mask 26 consists of a GaAs crystal having opposite end faces 27 and 27*a* cleaved to form mirror surfaces. The mask 26 is placed upon the layer 11 in such a way that the crystal surfaces of the mask 26 and the layer 11 are aligned. Thereafter, the wafer is subjected to reverse sputtering to remove the portions of the wafer delimited by the broken lines. Thus, a mesa type oscillator 10 is formed in the wafer as shown in step (iii) of Figure 7. The end faces of the oscillator 10 are cleaved to defined mirror surfaces in a similar manner to that in which the end faces 27 and 27*a* of the mask 26 are produced. Thereafter, as shown in step (iv) of Figure 7, the electrodes 14 and 25 are attached to the top and bottom of the wafer and the transparent insulating layers 15 and 15*a* are attached to the opposite end faces of the oscillator 10 followed by the addition of reflecting mirrors 16 and 16*a* to respective transparent insulating layers 15 and 15*a*. Thus, a multi-hetero-structure waveguide integrated optical circuit is obtained. Experimentally, it was found that if the mirror surfaces were obtained on the <110> surface of $Al_xGa_{1-x}As$ layer by the above method, a satisfactory laser action could be achieved.

In the integrated optical circuits shown in Figures 8 to 19 parts similar to those of Figure 1 are similarly referenced.

The circuit shown in Figure 8, includes an oscillator 10 which is not provided with reflecting mirror ends, but with distribution reflectors 28 and 28*a* supported on the upper surface of the waveguide circuit 20.

In the circuit shown in Figure 9 a reflecting mirror 27 is mounted on the waveguide 20 but spaced from the waveguide by a transparent insulating layer 26 in place of the reflector 28 of Figure 8.

The circuit shown in Figure 10, has reflecting mirror 27 formed integral with the oscillator 10.

In each of circuits of Figures 8 to 10 the width of the $Al_yGa_{1-y}As$ waveguide layer is equal to that of the layer below, but it will be appreciated that other widths can be selected.

The circuit of Figure 11 includes an output circuit 30 in addition to the oscillator 10 and the waveguide 20. The output circuit 30 which is a thin-film mode transformation circuit is formed on the waveguide 20 and direction-coupled thereto. In operation laser light from the oscillator 10 is transmitted through the

waveguide 20 to the output circuit 30, from which the laser light is transmitted through an optical fibre transmission line 70 to a remote destination.

The circuit of Figure 12 incorporates an amplifier 40 which is formed at the same time as the oscillator 10 by the reverse-sputtering technique referred to earlier in connection with step (i) of Figure 7. It will be seen that the laser active layers of the oscillator 10 and the amplifier 40 have the same composition which can be beneficial.

The circuit of Figure 13 includes in addition to the oscillator 10 and amplifier 40 formed on the waveguide 20, a modulator 50.

The electrode structure for the circuit of Figure 13 is shown in Figure 14. An elongate upper electrode 80 which also functions as a heat sink makes contact with the upper surface of each of the oscillator 10, the amplifier 40 and the modulator. Electrodes 81, 84 and 85 make contact with the under surface of the waveguide 20 directly below respective ones of the oscillator 10, the amplifier 40 and the modulator 50. Low resistance regions 81*a*, and 84*a* and 85*a* are formed by diffusion of impurities in the waveguide 20 directly adjacent respective ones of the lower electrodes 81, 84 and 85.

The circuit of Figure 15 includes a detector or demodulator 60 formed integral with the waveguide 20 of Figures 13 or 14. The detector 10 is formed from passive optical elements on the waveguide 20.

The optical circuit shown in Figure 16 includes an amplifier 40 formed integral with the waveguide 20. Thereafter an input circuit 30*a* and the output circuit 30 are formed on the waveguide.

The optical circuit shown in Figure 17 includes a filter 70 mounted between the amplifier 40 and the demodulator 60 of Figure 15. If in operation light from two oscillators operating at different frequencies f_1 and f_2 is transmitted along the waveguide 20, the filter 70 will act to suppress the light having a frequency f_2 so that the detector 60 will only receive light of frequency f_1.

The optical circuit shown in Figure 18 is arranged to operate as an arithmetic circuit utilizing a space Fourier transformation. The laser light from the oscillator 10 is transmitted through a thin-film lens 91 into a space modulator 92 and is modulated by a signal *g*. The modulated laser light is transmitted through a thin-film lens 93 into a space modulator 94 and is modulated by a signal *h*. The double modulated signal is then transmitted through a thin-film lens 95 into a detector bank 96 which provides (g×h) outputs. Each of the circuit components involved is formed as an integrated circuit.

The optical circuit shown in Figure 19 has a plurality of oscillators 10A to 10N formed in parallel on a waveguide so that the outputs therefrom may be added through a thin-film lens 97 to provide the high output.

Each of the circuits described uses a GaAs semiconductor laser however instead, any suitably hetero-structure diode laser such as an InGaAs, an AlGaAsSb, or an InGaAsP laser can be used. Also instead of the $AlGa_{1-z}As$ coupling layer, coupling layers of AlGaAsSb or InGaAs can be used.

WHAT I CLAIM IS:—

1. An integrated optical circuit comprising a multi-hetero-structure waveguide and a mesa type thin-film optical oscillator integrally formed through a directional coupler upon the waveguide, the dimensions of the oscillator and waveguide being so selected that the wavelength of the light signal generated by the oscillator can be coupled to the waveguide for transmission by the waveguide with substantially no initial loss.

2. An integrated optical circuit according to Claim 1, wherein said oscillator consists of a GaAs layer, an $Al_zGa_{1-z}As$ layer, an active layer consisting of Al_xGa_{1-x}, stacked one upon the other in the recited order, an electrode attached to the GaAs layer, and reflecting mirrors located at opposite ends of the stack faces but separated from the end faces by electrically insulating and translucent layers.

3. An integrated optical circuit according to Claim 1 or Claim 2, wherein the directional coupler consists of an $Al_zGa_{1-z}As$ layer, an AlGaAsSb layer or an InGaAs layer.

4. An integrated optical circuit according to any preceding claim, wherein the waveguide layer consisting of $Al_yGa_{1-y}As$ layer contacting the coupler, a GaAs layer contacting the Al_yGa_{1-y} layer and an electrode attached to the GaAs layer.

5. An integrated optical circuit according to Claim 4, wherein a distribution type reflector is formed integral with the $Al_yGa_{1-y}As$ layer of the waveguide.

6. An integrated optical circuit according to any preceding claim including a reflecting mirror formed on one longitudinal end face of the waveguide.

7. An integrated optical circuit according to any one of the preceding claims, including a thin-film mode-matching output circuit formed integral with the waveguide and direction-coupled thereto at a location spaced from the oscillator.

8. An integrated optical circuit according to any preceding claim including an

amplifier formed integral with the waveguide at a location spaced from the oscillator.

9. An integrated optical circuit according to any preceding claim including a plurality of further oscillators each similar to the first mentioned oscillator and each coupled in a similar manner as the first mentioned oscillator to the waveguide at spaced locations whereby the output of all the oscillators are coupled in parallel to the waveguide.

10. An integrated optical circuit according to any preceding claim including a modulator formed integral with the waveguide at a location spaced from the oscillator.

11. An integrated optical circuit according to Claim 10 including a demodulator formed integral with the waveguide at a location such that an optical signal from the oscillator passes through the modulator before reaching the demodulator.

12. An integrated optical circuit according to Claim 11 including a filter formed integral with the waveguide at a location such that said optical signal passes through the filter after passing through the modulator but before passing through the demodulator.

13. A method of making an integrated optical circuit comprising the steps of preparing a multi-layered wafer consisting of a first layer of GaAs, a second layer of $Al_zGa_{1-z}As$, a third layer of $Al_xGa_{1-x}As$, a fourth layer consisting of $Al_zGa_{1-z}As$ and constituting a coupling layer, a fifth layer consisting of $Al_yGa_{1-y}As$ and constituting an output waveguide, a sixth layer consisting of $Al_zGa_{1-z}As$ and a seventh layer of GaAs, the first to seventh layers being stacked one on top of the other in the recited order from the top to the bottom; placing a mask on the first layer; back-sputter-etching the wafer so as to remove the unmasked layers above the layer half portion of the coupling layer consisting of $Al_zGa_{1-z}As$ thereby forming a mesa type oscillator; thereafter finishing the opposite end faces of the first to third layers to have a mirror surface; attaching transparent insulating layers upon the said end faces and forming reflecting mirrors on the transparent insulating layers to complete the formation of a mesa type oscillator, the dimension of said layers being so selected that the wavelength of the light signal generated by the oscillator can be coupled to the waveguide for transmission by the waveguide with substantially no initial loss.

14. A method according to Claim 13, wherein said mask consists of a GaAs crystal whose ends are cleaved to provide mirror surfaces, and is placed on the first GaAs layer of the oscillator in such a way that the contacting crystal surfaces are aligned.

15. An integrated optical circuit substantially as hereinbefore described with reference to Figures 1 to 6.

16. An integrated optical circuit substantially as hereinbefore described with reference to Figure 8.

17. An integrated optical circuit substantially as hereinbefore described with reference to Figure 9.

18. An integrated optical circuit substantially as hereinbefore described with reference to Figure 10.

19. An integrated optical circuit substantially as hereinbefore described with reference to Figure 11.

20. An integrated optical circuit substantially as hereinbefore described with reference to Figure 12.

21. An integrated optical circuit substantially as hereinbefore described with reference to Figures 13 and 14.

22. An integrated optical circuit substantially as hereinbefore described with reference to Figure 15.

23. An integrated optical circuit substantially as hereinbefore described with reference to Figure 16.

24. An integrated optical circuit substantially as hereinbefore described with reference to Figure 17.

25. An integrated optical circuit substantially as hereinbefore described with reference to Figure 18.

26. An integrated optical circuit substantially as hereinbefore described with reference to Figure 19.

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FIG. 1

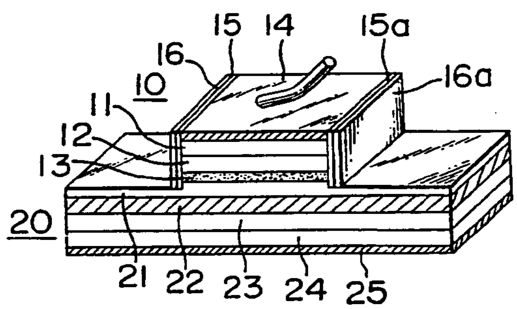

FIG. 2

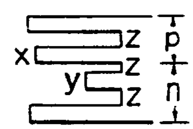

FIG. 3

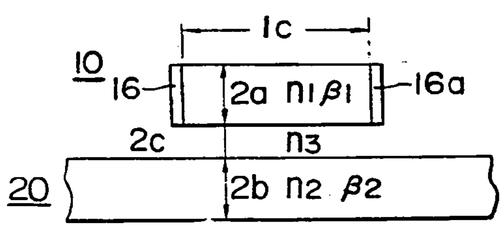

FIG. 4

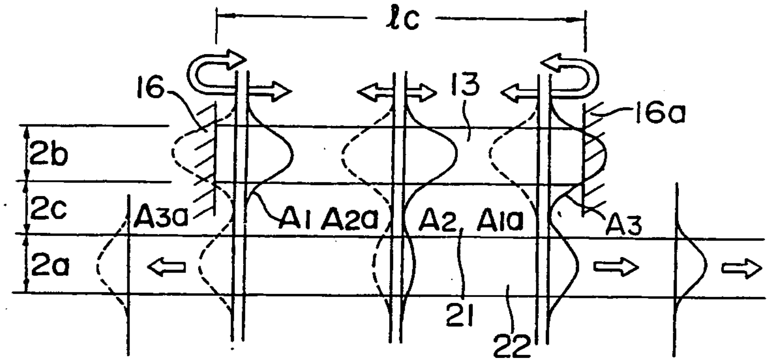

FIG. 5

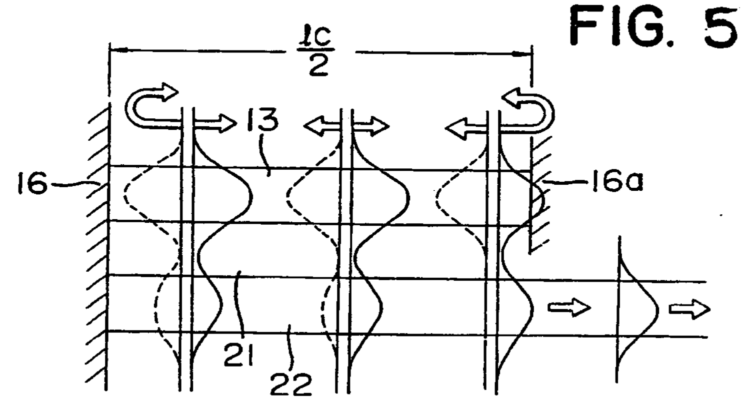

FIG. 6(a)

$\beta_1=\beta_2$

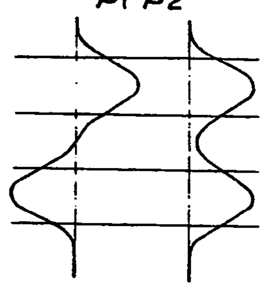

FIG. 6(b)

$\beta_1\neq\beta_2$

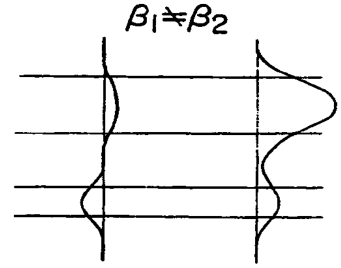

FIG. 7

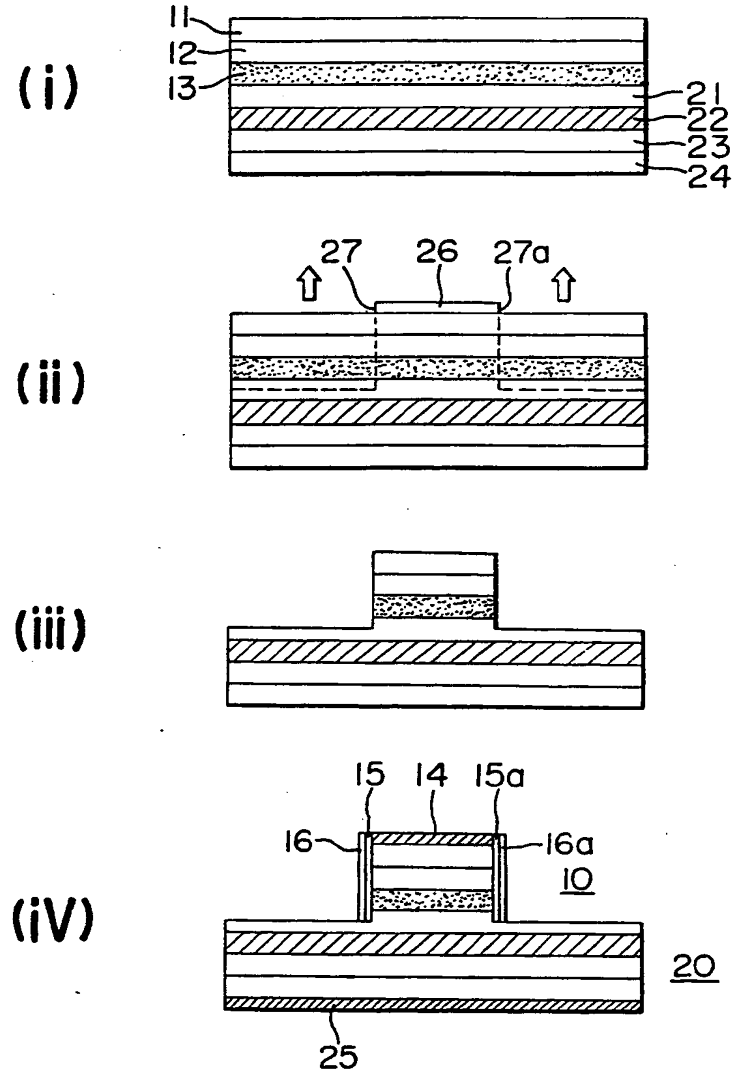

FIG. 8

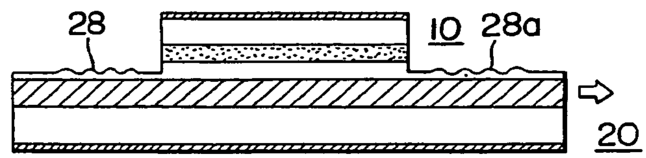

FIG. 9

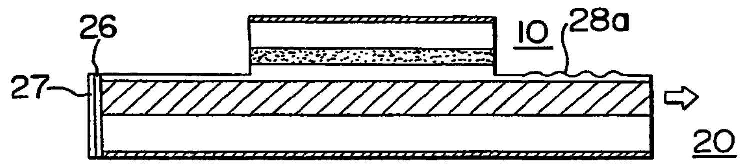

FIG. 10

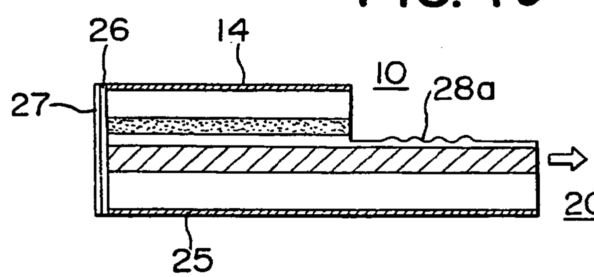

FIG. 11

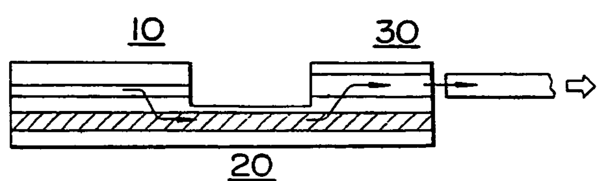

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FIG. 12

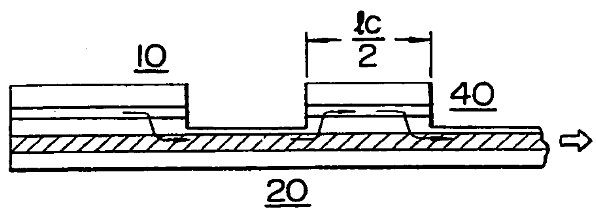

FIG. 13

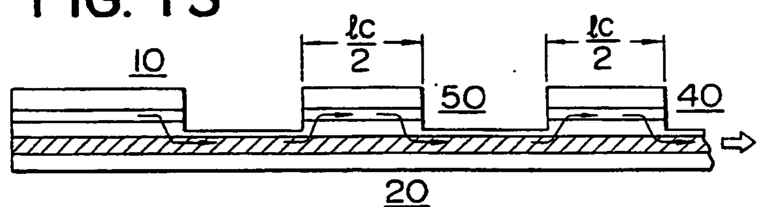

FIG. 14

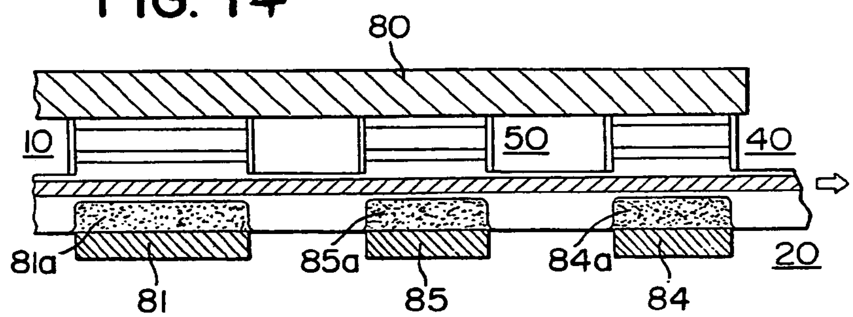

FIG. 15

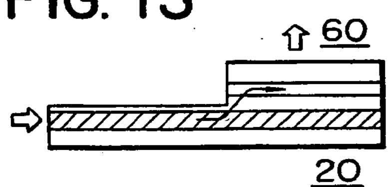

FIG. 16

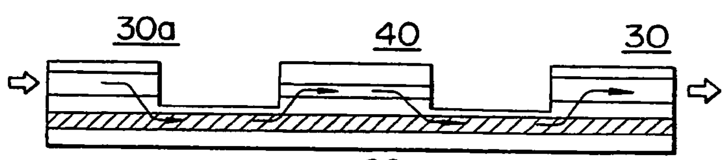

FIG. 17

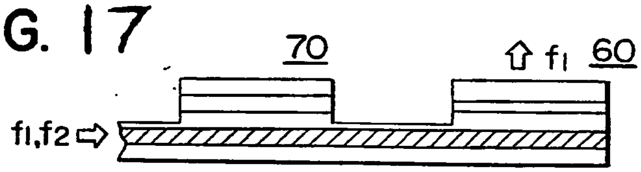

FIG. 18

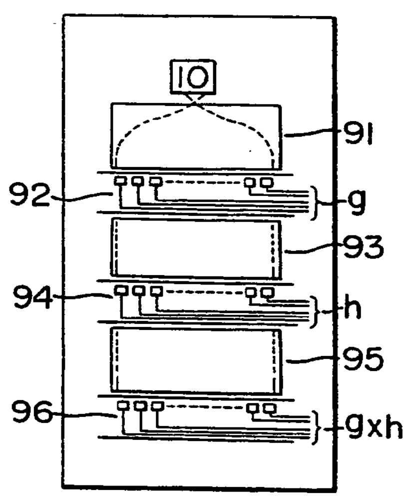

FIG. 19

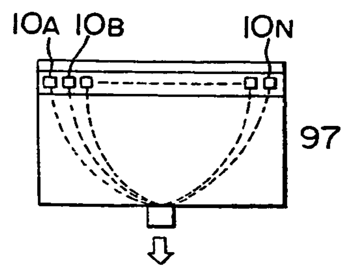

FIG. 1

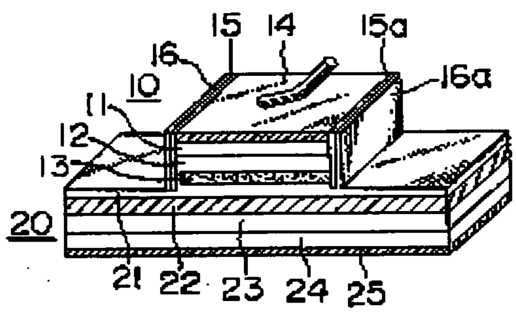

FIG. 2

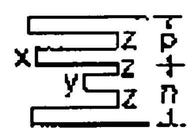

FIG. 3

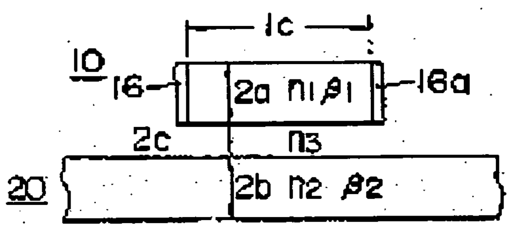

FIG. 4

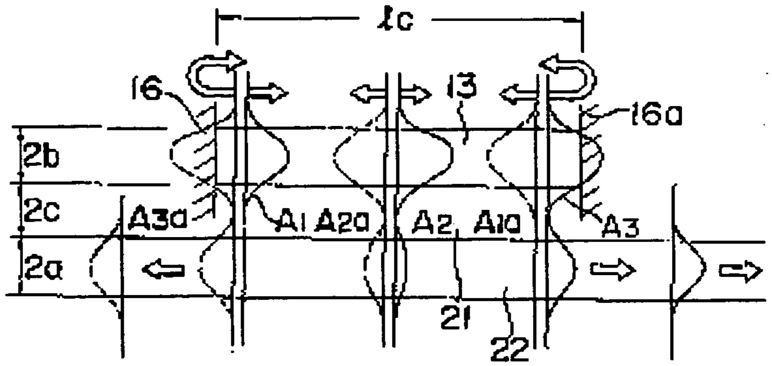

FIG. 5

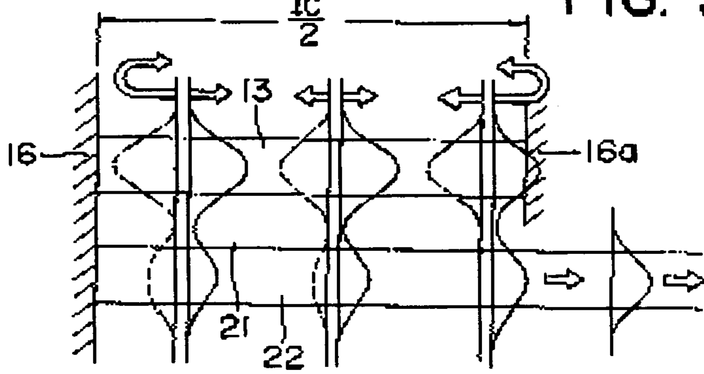

FIG. 6(a)

$\beta_1 = \beta_2$

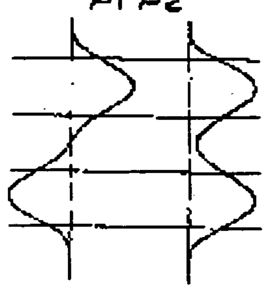

FIG. 6(b)

$\beta_1 \neq \beta_2$

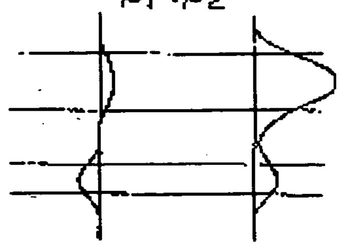

FIG. 7

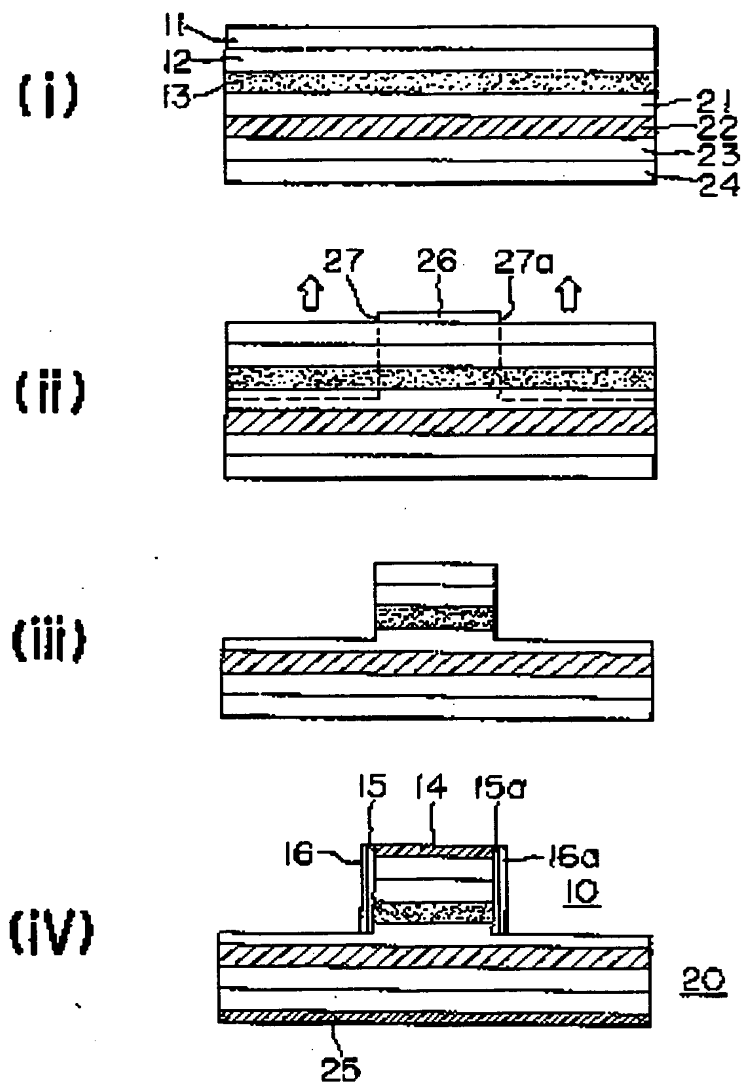

FIG. 8

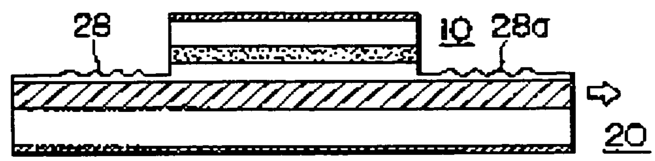

FIG. 9

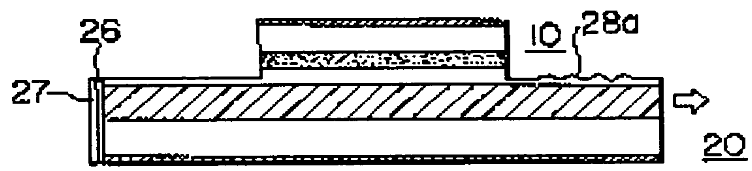

FIG. 10

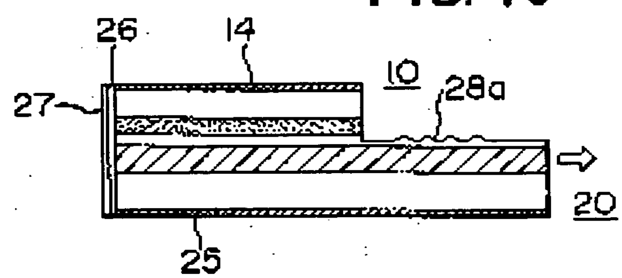

FIG. 11

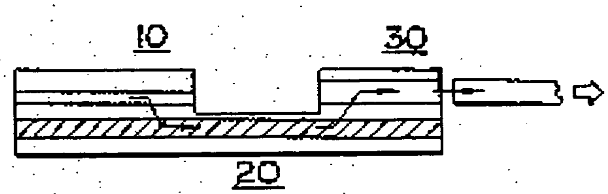

FIG. 12

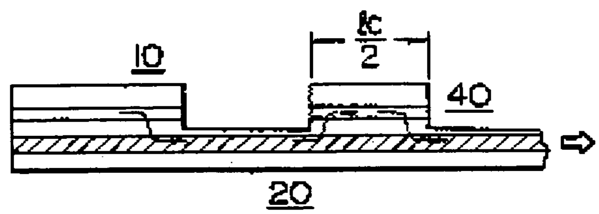

FIG. 13

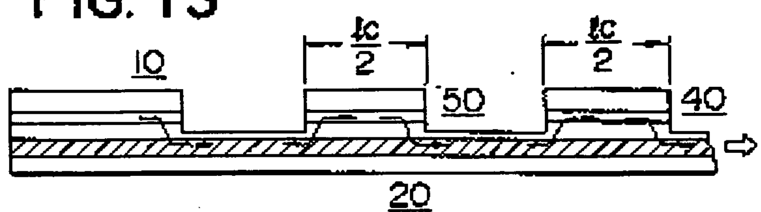

FIG. 14

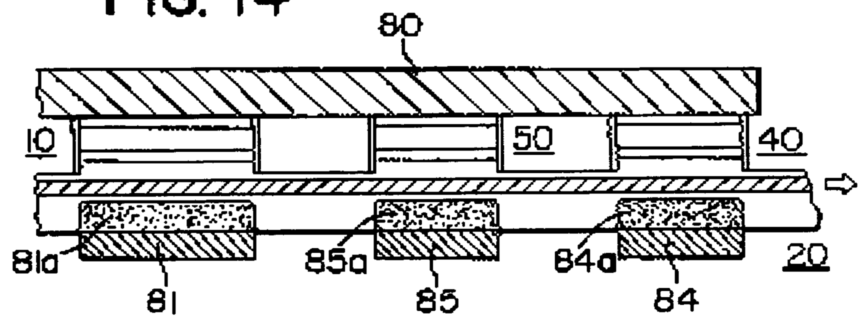

FIG. 15

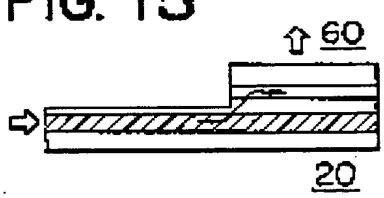

FIG. 16

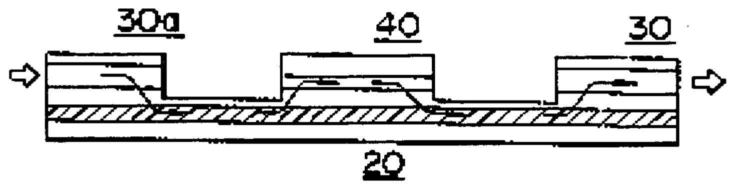

FIG. 17

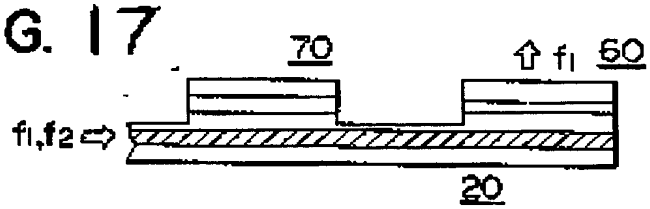

FIG. 18

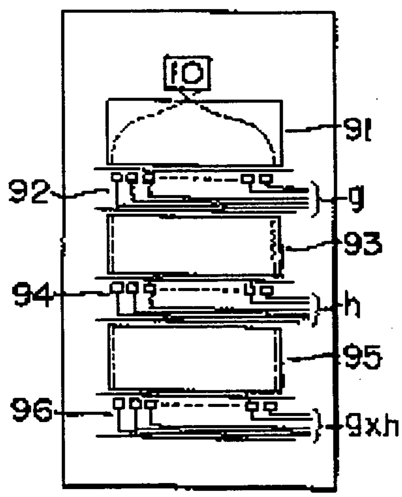

FIG. 19